AN INITIAL FORAY INTO THE PRODUCTIVE APPLICATION OF COMPUTATIONAL FLUID DYNAMICS

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13. ABSTRACT *(Maximum 200 Words)*
    A suite of Government-developed, productivity-oriented, Computational Fluid Dynamics software has been constructed for use in the aerodynamic design of missiles. This suite is based on a robust Eulerian solver, and it uses automated grid generation to drastically reduce the time required to set up flowfield computations. The software is described and then applied to two potential hypervelocity missile configurations: one using a bent nose for aerodynamic control and the other using traditional canards. Comparisons mad with wind tunnel data demonstrate the ability of the software suite to produce meaningful results for use by aerodynamic designers.

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I. INTRODUCTION

The aerodynamic design of missiles requires the use of predictions tools that respond quickly to constantly changing system parameters. In the preliminary design phase, semi-empirical methods such as Missile DATCOM [1], AP98[2], and Missile3[3] are useful for conducting trade studies and establishing initial configuration geometries. This is because they can provide aerodynamic characteristics for numerous potential airframes at a multitude of flight conditions—all within a few minutes.

However, in the intermediate design phase, it is typical to need more general capabilities and a higher degree of modeling fidelity than can be provided by these kinds of tools. For this part of the design process, the missile aerodynamicist must select from a plethora of approaches ranging from piecemeal solutions (such as S/HABP[4]) and panel methods (such as CMARC[5] and PANAIR[6]) to marching techniques (a la ZEUS[7] and parabolized Navier-Stokes codes) and full-field, elliptical, Computational Fluid Dynamics (CFD) approaches (typified by various potential flow, Eulerian, and Navier-Stokes solvers).

While the full-field, elliptical, CFD methods offer very general capabilities and high degrees of modeling fidelity, they usually require substantial amounts of time in their utilization. For these techniques, one must generate the solution grid, establish boundary conditions on the grid, determine appropriate input parameters and code options for the solver, execute the solver on a computer (often a supercomputer), assess the convergence of the solution, and extract the required aerodynamic characteristics from the converged solution (typically by integrating the pressure field). Such a process requires specialized knowledge in grid generation and thorough familiarity with the specific solver(s) being applied. The need for such in-depth, focused knowledge means that computational specialists, not aerodynamic designers, must exercise these types of tools in order to use them efficiently. However, the lengthy time required to use these approaches makes them generally unresponsive when airframe design features change regularly as they do in the intermediate design phase.

This means that the missile aerodynamicist is limited in a practical sense to the other types of intermediate level tools. These approaches require less in-depth, specialized training to use them, and they generally execute in a modest amount of time on small computers. However, each method is somewhat restricted in its range of applicability. For example, S/HABP and ZEUS and are restricted to the supersonic and hypersonic flow regimes while CMARC is limited to incompressible flow. And although PANAIR works for both subsonic and supersonic flows, neither it nor any of the other non-elliptical formulations are able to address transonic flow. These techniques are able to respond to design changes in a more timely manner than full-field, elliptical methods. However, they must be used in a piecemeal fashion to construct a complete aerodynamic characterization for the entire flight of a proposed missile. Since each method requires the airframe geometry to be created in its own particular format, the time required to use these tools becomes significant in the design environment.

There is clearly a need for a contiguous, generally capable, high fidelity, responsive, intermediate level aerodynamic design tool. Such a single, all-encompassing approach would greatly enhance the productivity of the aerodynamicist. To address this need, a suite of

specialized tools has been assembled within a single framework dubbed the Euler Tunnel Analysis (ETA) by its developer, the Missile and Space Intelligence Center (MSIC). The Aviation and Missile Research, Development, and Engineering Center (AMRDEC) of the U.S. Army Research, Development, and Engineering Command (RDECOM) is using this tool in the design of a proposed hypervelocity missile. The features of this tool and comparisons of its predictions with data (both Navier-Stokes computations and wind tunnel measurements) for the proposed missile will be described in the following sections of this paper.

II. METHODOLOGY

A. Description

ETA is a suite of Government-owned, productivity-oriented, CFD software developed to facilitate aerodynamic design and analysis. It uses a geometry generation code, named CFDGEN, that was developed by MSIC to construct geometries from a library of pre-existing models and model parts. CFDGEN does not require Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) expertise, and this feature makes the construction of body geometries tractable for the aerodynamic designer.

ETA utilizes the NASA/Ames Cart3D[8] methodology developed by Aftosmis, Melton, and Berger to create an unstructured, Cartesian field grid around the body geometry in an automated fashion. Cart3D, itself a suite of tools, can import geometries in various unstructured and structured formats, including the NASA Langley Wireframe Geometry Standard (LaWGS) format produced by CFDGEN. It then adaptively refines Cartesian grid cells around the body, and cuts the body out of the set of cells that actually intersect it. This process typically takes less than an hour; a attribute that saves countless man-hours in grid generation time and substantially enhances productivity.

The flow solver element of ETA is the TIGER[9] code developed by Melton. TIGER is an unstructured, finite-volume, Eulerian, CFD code. It uses Jameson's [10] four-stage, Runge-Kutta, time integration algorithm which has proven itself to be quite robust as implemented in TIGER. The particular version of TIGER used in ETA has been modified by Robinson[11] to (1) permit the use of an algebraic enthalpy equation (in lieu of the differential energy equation), (2) permit the specification of the desired number of Runge-Kutta integration stages that will be computed, and (3) enhance its robustness near corners and other high-gradient regions at high Mach numbers. These alterations reduce computation time and increase TIGER's reliability, further enabling the aerodynamicist to be productive.

Although each of the above parts of ETA increases the productivity of the aerodynamic designer, the primary mechanism that makes this CFD technology amenable to the fast-paced aerodynamic design environment is its Graphical User Interface (GUI) and utility software scripts. These components allow the designer to readily edit the baseline geometry and create configurations with desired control deflections angles. The GUI and scripts also (1) establish the directory structure and flow solver input files (based on Mach number, roll angle, and angle of attack) for each aerodynamic point of interest, (2) submit each case to the computational platform, (3) check the run status of each case, (4) bring the results back from the computational

platform, and (5) compute aerodynamic coefficients from the flowfield solution for each point of interest. It is this high degree of automation that increases the usefulness of CFD to the point of practical, productive application to aerodynamic design.

B. Application

ETA was applied to the aerodynamic design of the two potential, eight-finned hypervelocity missile configurations shown in Figures 1 and 2. The first of these uses a bent nose to effect aerodynamic control while the second is equipped with conventional canards. The geometries for each airframe were constructed with CFDGEN from wind tunnel model blueprints. The actual three-dimensional fin (and canard) thickness, leading edge radius, thickness taper, and breakline sweep angles were all included in the constructed models. Only a single baseline geometry was needed for the canard-controlled airframe (the undeflected case), but individual representations were required for each of the nose deflection angles for the bent nose configuration.

Figure 1. Three-Dimensional CFDGEN Model of Bent-Nose Configuration Deflected 8 Degrees
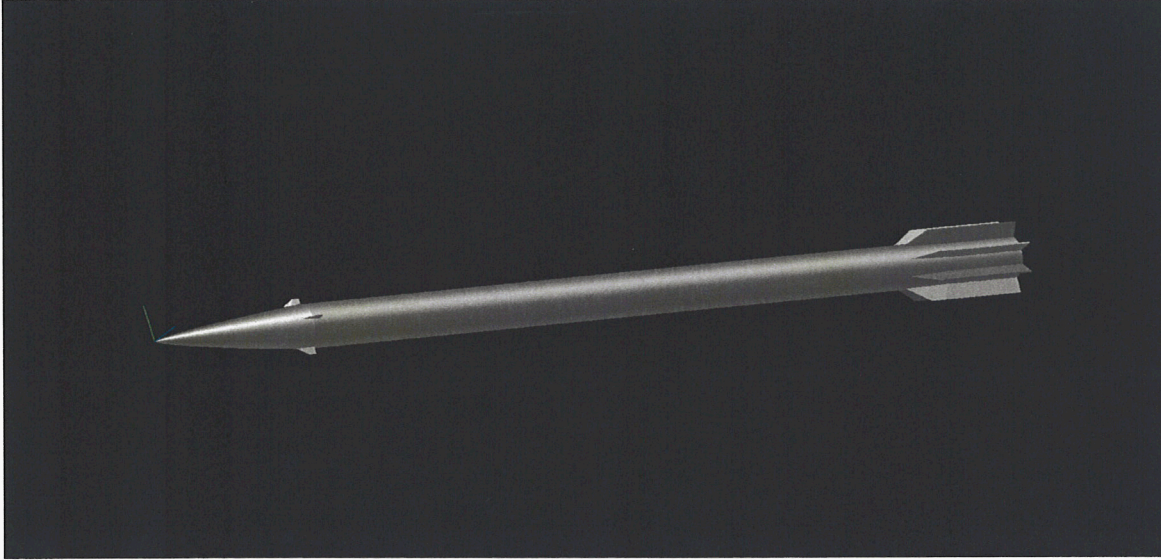
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Figure 2. Three-Dimensional CFDGEN Model of Canard-Controlled Configuration

The ETA GUI (Fig. 3) was used to control execution of the Cart3D conversion utilities for each missile geometry. And this was done in a straightforward, intuitive, point-and-click fashion. The GUI was also used to invoke the Cart3D grid generation code, named cubes, and to exercise the cart2tiger tool to convert the grid into a TIGER-compatible format.
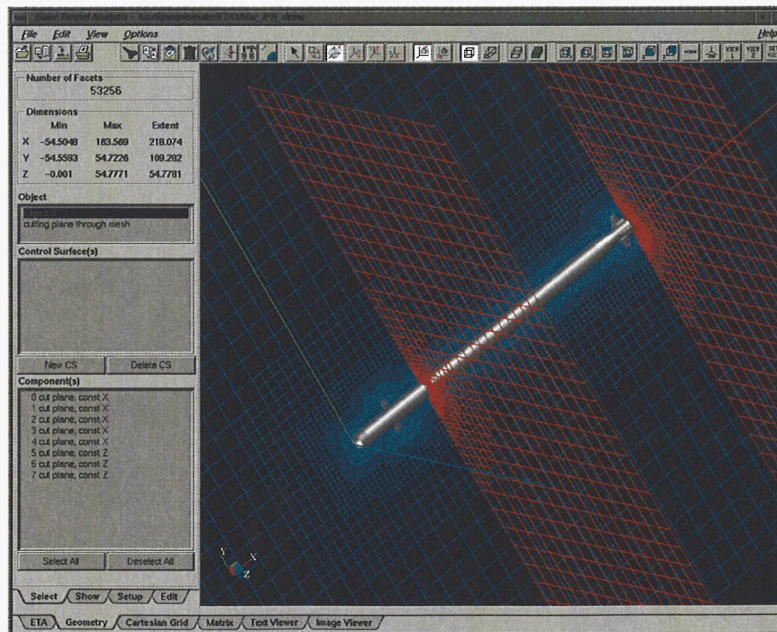

Figure 3. ETA GUI Geometry Tab

For each bent-nose model, the input to cubes was set to create a field grid with the upstream boundary 0.19 body lengths away and the other boundaries from 1.5 to 1.9 lengths away as shown in Figure 4. Freestream boundary conditions were chosen for them. The minimum grid cell dimensions were set to approximately one one-thousandth (1/1000) of the

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body length and 6 levels of grid refinement were specified. These parameters produced grids with approximately one million (1,000,000) Cartesian cells.
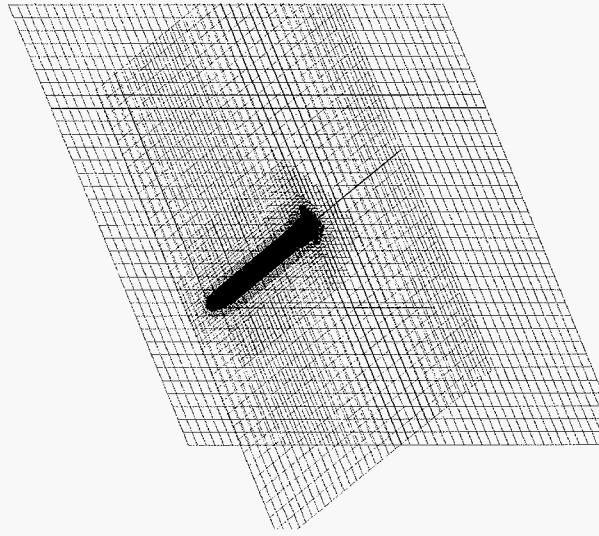

Figure 4. Cart3D Field Grid for 8 Degree Bent-Nose Configuration

For the canard-controlled missile, the initial grid was constructed similarly. However, the need to capture the canard/tail vortex interactions necessitated a much smaller minimum cell size. Several sizing approaches were tried, with the most successful one locating the downstream boundary two body lengths away and each of the other boundaries one length away as shown in Figure 5. The minimum cell size was set to one-eleventh (1/11) of the exposed semi-span of the canard in the lateral and vertical directions while remaining one one-thousandth (1/1000) of the body length in the longitudinal direction. The ability of cubes to specify adaptation regions was invoked to constrain most of the cell refinement to the region between the canards and the tail fins, including the volume between the fins themselves. The corresponding cubes input parameters produced a grid with 5,058,468 cells.
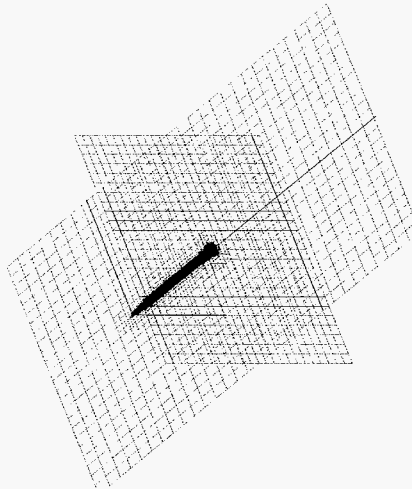

Figure 5. Cart3D Field Grid for Canard-Controlled Configuration

Upon completion of the grid generation (which took less than one hour for each case), the ETA GUI and scripts were used to specify the Mach number, roll angle, and angle of attack combinations to use in computing flowfields for each missile configuration. The GUI and scripts were also used to select the TIGER input parameters, create the required directory structure on the local workstation (a Silicon Graphics O200), transfer the required geometry and input files to the remote supercomputer (a Cray SV-1), submit the runs for each case, check the status of each run, download the results of each computation, compute the aerodynamic coefficients for each case, and create ASCII plot files of each angle of attack sweep. For the bent-nose missile, flowfields and aerodynamic coefficients were computed for a Mach number of 3.0; roll angles of 0, 45, and 90 degrees; and angles of attack from –10 to +10 degrees in 2-degree increments. Computations for the canard-controlled missile were made at Mach numbers 3.0 and 4.5; a roll angle of 0 degrees; and angles of attack from –10 to +10 degrees in 2-degree increments.

III. RESULTS AND DISCUSSION

Results for the bent-nose configuration are presented in the body-fixed reference frame and compared with wind tunnel data[12] in Figures 6 through 9. These ETA predictions were performed "blind" without examining any of the measurements. It is evident from Figures 6 and 7 that the ETA values for normal force and pitching moment agree quite well with the data for each of the bent-nose deflections. In particular, the pitching moment agrees very well, especially since it is referenced well downstream of the nose (a condition that amplifies prediction discrepancies). It should also be noted in Figure 7 that the Eulerian predictions of ETA begin to deviate from the measurements when the sum of the angle of the nose deflection and the angle of attack begin to exceed 10 degrees. This behavior is expected since viscous forces are likely to affect leeward flow separation above moderate total angles of attack.
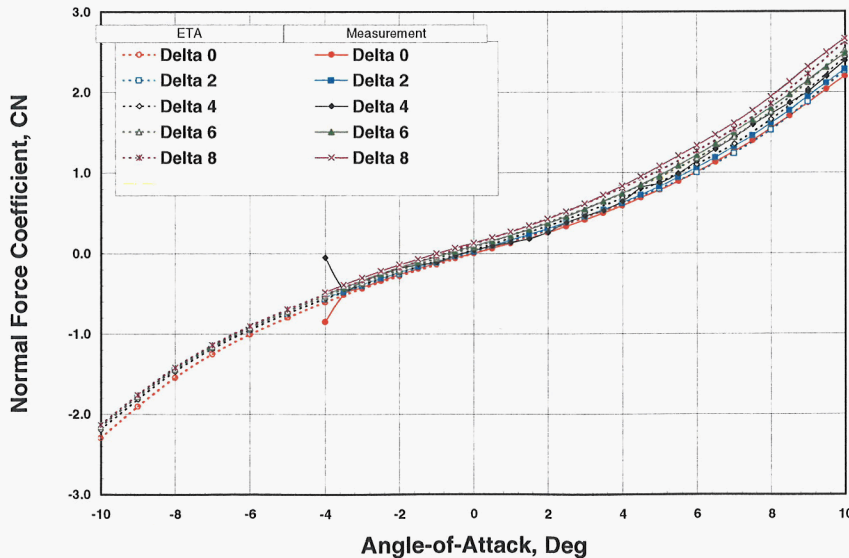

Figure 6. Normal Force Coefficient Versus Angle of Attack for All Bent-Nose Configurations
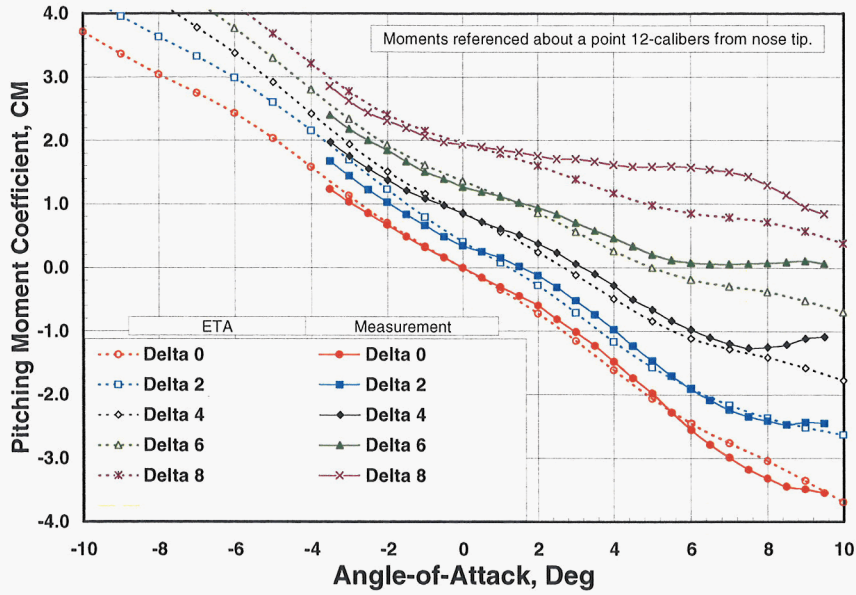
Figure 7. Pitching Moment Coefficient Versus Angle of Attack for All Bent-Nose Configurations

The ability of the ETA methodology to use the same solution grid to address missiles flying in a rolled attitude is shown in Figures 8 and 9. For these 45- and 90-degree roll attitudes, the normal force and pitching moment curves were nearly coincident with measurements; they were not presented to save space. Rather, the more demanding comparison of yawing moment is provided in these two plots. It can be seen that the agreement with measurement is again quite good up to about 4 degrees angle of attack, above which it is expected that viscous forces affect the leeward flow as mentioned before.
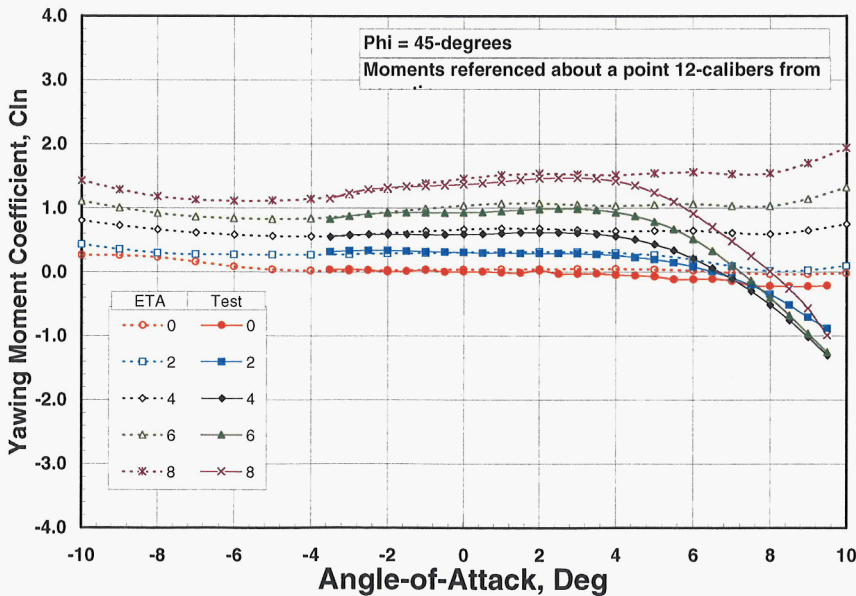

Figure 8. Yawing Moment Coefficient Versus Angle of Attack for All Bent-Nose Configuration at 45-Degrees Roll
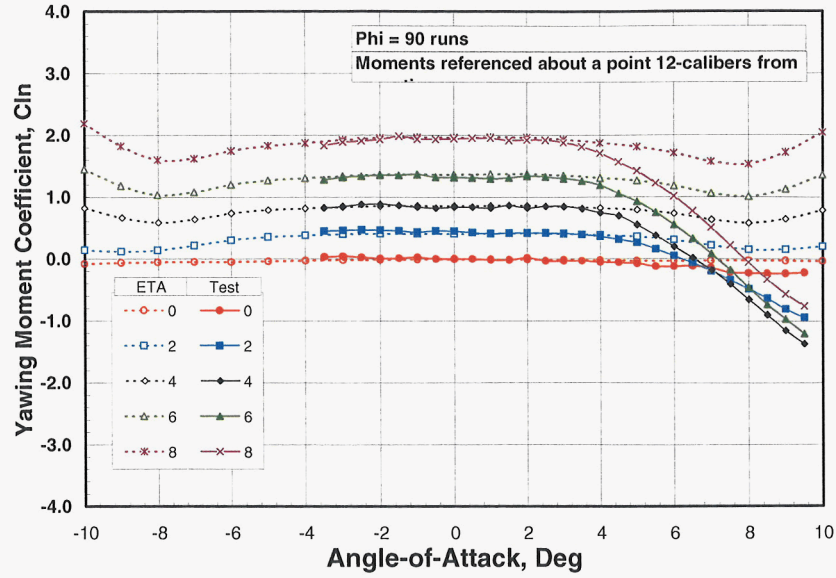
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Figure 9. Yawing Moment Coefficient Versus Angle of Attack for All Bent-Nose Configurations at 90-Degrees Roll

The results for the canard-controlled missile are exhibited in Figures 10 and 11. As previously stated, initial computations were performed using the "1/1000th" body length rule to construct the solution grid. However, the predictions made for Mach 4.5 completely missed the drastic change in the pitching moment curve shown in Figure 10. It was reasoned that interactions between the canard vortices and the tail fins were the cause of such a change and that the grid was insufficiently resolved to capture these interactions. After several attempts at determining appropriate cell sizing criteria, it was found that the approach described in the previous section produced satisfactory agreement with the pitching moment data. Figure 11 shows the same type of normal force and pitching moment comparison for Mach 3.0. This plot also shows a slight change in the moment curve, which is similarly captured by the ETA calculations using the same solution grid.
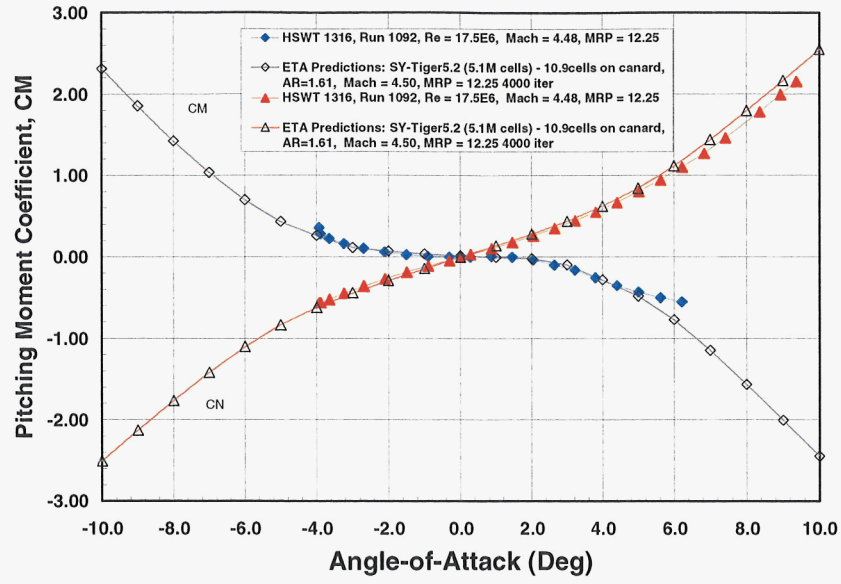
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Figure 10. Normal Force and Pitching Moment Coefficients Versus Angle of Attack for Canard-Controlled Configuration at Mach 4.5, 0-Degrees Roll
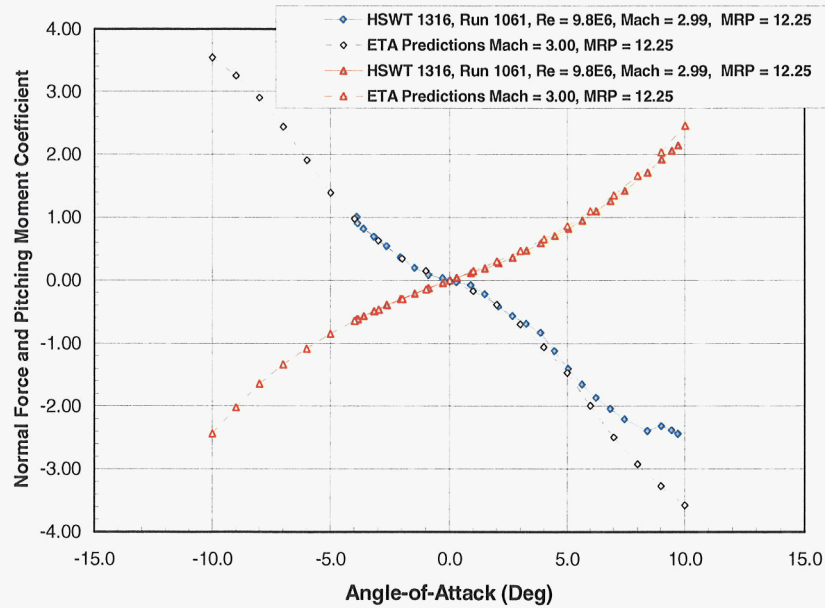

Figure 11. Normal Force and Pitching Moment Coefficients Versus Angle of Attack for Canard-Controlled Configuration at Mach 3.0, 0-Degrees Roll

IV. SUMMARY

ETA has shown itself to be a powerful tool in the application of CFD to aerodynamic design. Its use of the Cart3D automated grid generation tool in conjunction with the robust TIGER Eulerian flow solver make it possible to use CFD in a timely manner. By centralizing user interactions within its GUI and by using scripts to automate many administrative processes, ETA reduces user error and enhances productivity.

Comparisons of ETA predictions with wind tunnel data for two complex missile configurations have further demonstrated its value. In order to make them, ETA had to produce angle of attack sweeps in a reasonable time. It often generated an alpha sweep (11 data points for the bent nose, 17 points for the canard missile) overnight when running on a Cray-SV1. Each bent-nose calculation was executed for approximately 8 CPU hours, and each canard-missile computation was run for around 24 CPU hours. The results of these predictions speak for themselves in showing ETA's ability (1) to properly characterize the aerodynamics of a bent-nose missile at various angles of attack and roll attitudes, and (2) to accurately capture the effects of canard/tail vortex interactions on pitching moment. ETA is not a panacea, however, as it has the physical limitations of an Eulerian solver. Nonetheless, it is a unified means by which the missile aerodynamicist can productively characterize the more prominent flight characteristics of complex missile designs. As such, it is expected to become a "workhorse" at the AMRDEC.

REFERENCES

1. Vulelich, S. R., Stoy, S. L., Burns, K. A., Castillo, J. A., and Moore, M. E., "Missile DATCOM Volume I – Final Report," AFWALTR-86-3091, December 1988.

2. Moore, F. G., Mcinville, R. M., and Hymer, T., "The 1998 Version of the NSWCDD Aeroprediction Code: Part II – Program User's Guide and Source Code Listing," NSWCDD/TR-98/73, May 1998.

3. Lesieutre, D. J., Love, J. F., and Dillenius, M. F. E., "MISL3 – November 2000 Aerodynamic Analysis for Finned Vehicles with Axisymmetric Bodies," NEAR TR 561, May 2001.

4. Gentry, A. E., Smyth, D. N., and Oliver, W. R., "The Mark IV Supersonic-Hypersonic Arbitrary Body Program, Volume I Users Manual," Technical Report AFFDL-TR-73-159, November 1973.

5. AeroLogic, "Digital Wind Tunnel CMARC Three-Dimensional Low Order Panel Codes," 2000.

6. Magnus, A. E. and Epton, M. A., "PAN AIR – A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations Using A Higher Order Panel Method," Vol. I Theory Document (Version 1.0), NASA CR-3251, 1980.

7. Wardlaw, A. B. and Davis, S. F., "A Second Order Godunov Method for Supersonic Tactical Missiles," NSWC TR 86-506, December 1986.

8. Aftosmis, M. J. and Berger M. J., "Multilevel Error Estimation and Adaptive h-Refinement for Cartesian meshes with Embedded Boundaries,' AIAA Paper 2002-0863, January 2002.

9. Melton, J. E., Berger, M. J., and Aftosmis, M. J., "3D Applications of a Cartesian Grid Euler Method," AIAA Paper 95-0853, 1995.

10. Jameson, A., Schmidt W., and Turkel, E., "Numerical Solutions of the Euler Equations by Finite Volume Methods Using Runge-Kutta Time-Stepping Schemes," AIAA Paper 81-1259, June 1981.

11. Robinson, M. A., "Modifications of SY-TIGER code → Version 5.3 Release Notes & Guide,' SY Technology, Memorandum, 27 April 2002.

12. Auman, L. M. and Landers, M. G., "Aerodynamic Characteristics of the AMCOM Separating CKEM Concept," U.S. Army Aviation and Missile Command TR-RD-SS-02-09, June 2002.

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